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AN ESTIMATE OF THE SOLAR CYCLIC VARIATION OF THE MARTIAN UPPER ATMOSPHERE

D. N. VACHON, D. WEIDNER, K. LICHTENFELD

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AUTHOR
D.N. VACHON
D.K. WEIDNER
K. LICHTENFELD

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SUMMARY

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The results indicate that the Martian atmospheric density at 1,000 kilometers during a period of high solar activity is likely to be three orders of magnitude greater than it is during a period of low solar activity. The results therefore suggest that the upper atmosphere density profile inferred from the Mariner IV fly-by experiments is likely to be substantially different from that which will be inferred from the Mars '69 experiments.

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AN ESTIMATE OF THE SOLAR CYCLIC VARIATION OF THE MARTIAN UPPER ATMOSPHERE*

by

D. N. Vachon, Meteorologist, Aerospace Physics Laboratory, GE-MSD

D. Weidner, Meteorologist, Space Environment Branch, NASA-MSFC

K. Lichtenfeld, Physicist, Aerospace Physics Laboratory, GE-MSD

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ABSTRACT

A semi-empirical model of the Martian atmosphere is presented. This model is modified by means of an empirical formulation to provide an estimate of probable cyclic variations in the Martian upper atmosphere. The resulting variations are compared to those encountered in the Earth's atmosphere and on this basis appear reasonable.

The results indicate that the Martian atmospheric density at 1,000 kilometers during a period of high solar activity is likely to be three orders of magnitude greater than it is during a period of low solar activity. The results therefore suggest that the upper atmosphere density profile inferred from the Mariner IV fly-by experiments is likely to be substantially different from that which will be inferred from the Mars '69 experiments.

SECTION 1

INTRODUCTION

Defining the density profile of the Martian upper atmosphere is somewhat of a problem, since it can be expected that the structure of the outer atmosphere will be greatly influenced by solar variations in much the same manner as is the Earth's atmosphere. It is expected that the density at high altitudes (greater than 200 km) will be greatest during periods of high solar activity, as is the case in the Earth's upper atmosphere. Thus, an estimate of the probable solar cyclic-related variation of the upper atmosphere of Mars can be of assistance in reducing the uncertainty range of density variation likely to be experienced in any given year. In addition, such an estimate would provide a means of relating derived density profiles from fly-by experiments made at different periods of time.

The purpose of this paper is to:

a. Present a brief discussion of the probable time-space variations of the outer atmosphere.

b. Present a semiempirical model of the outer atmosphere of Mars.

c. Develop, by empirical means, a method of reducing density uncertainties associated with a given model by allowing for solar cyclic variations.

SECTION 2
MEAN ATMOSPHERE MODEL

A mean model and associated extreme envelopes has previously been developed by D. Weidner in 1967 and Weidner and Hasseltine in 1967. The model was based in part on the results of a number of theoretical studies on the structure and chemical kinetics of the atmosphere, (e.g. Chamberlain and McElroy - 1966, Donahue - 1966, Fjeldbo, et al. - 1966, Johnson - 1965, and Smith and Beutler - 1966). The results of others were thus taken into account in the study which included consideration of: the various interpretations of the Mariner IV data, the diffusion and possible escape of the Martian exospheric gases, the relationship of temperature and exospheric constituent distribution, the probability of mixing between the space plasma and the Martian exosphere, and the dependency of the exospheric temperature on solar activity.

The result of the study was the development of a mean atmosphere model which is consistent with the present level of knowledge. The altitude variation of temperature, molecular weight, and density provided by the model are presented in Figure 2-1, 2-2, and 2-3 respectively. Significantly, the molecular weight profile (Figure 2-2) contains the attractive feature of allowing for values below 16 which typically is the lowest value obtained in most studies of the chemical kinetics of the Martian atmosphere. The reason for the latter is due to the inclusion of only the major species of interest, whereby hydrogen and helium species are inevitably excluded. Thus, the outer reaches of the atmosphere are shown to be rich in atomic oxygen which is the lightest the species considered.

The density profile, Figure 2-3, contains the envelope of the minimum and maximum density expected to be encountered at high altitudes. The relation of these density envelopes to solar activity can be inferred through use of empirical methods, which are discussed in the following sections.

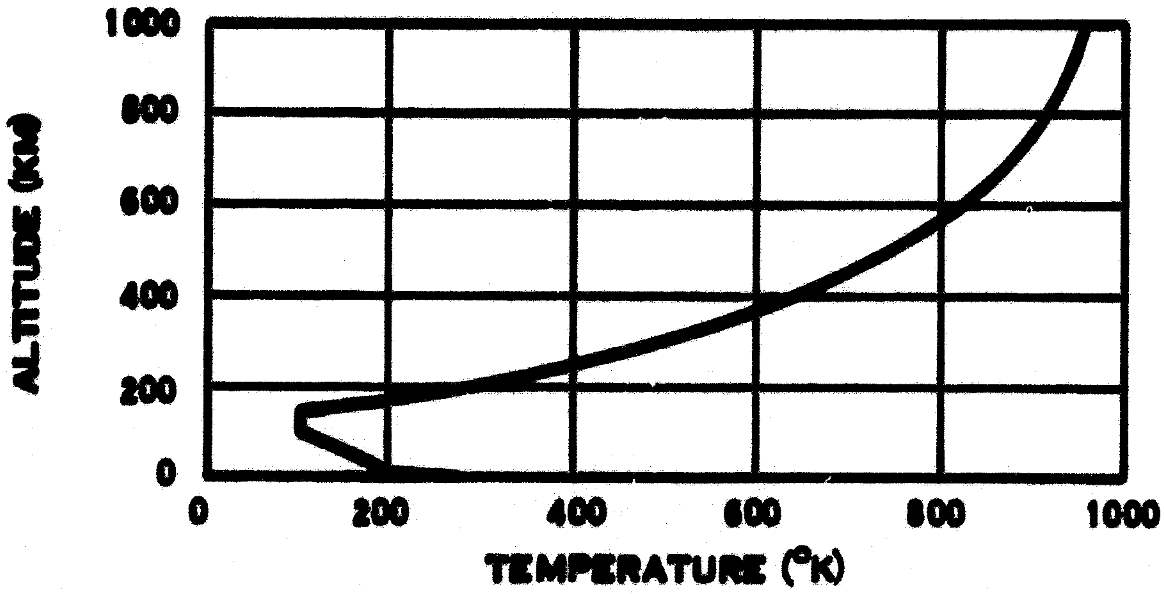

Figure 2-1. Temperature Profile in Mean Atmosphere Model of Mars

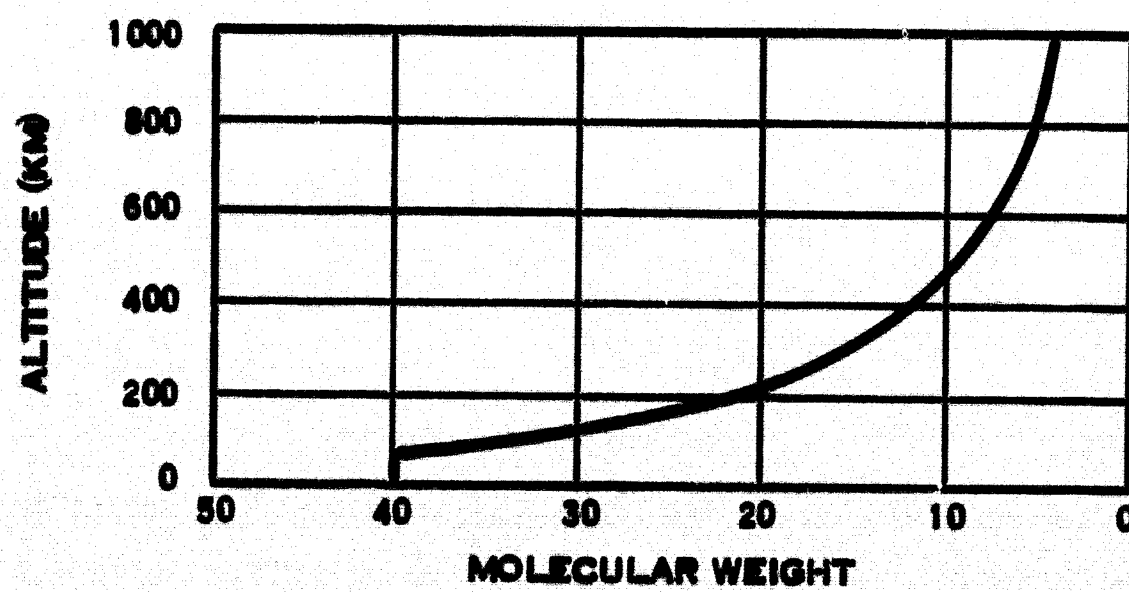

Figure 2-2. Molecular Weight Profile in Mean Atmosphere Model of Mars

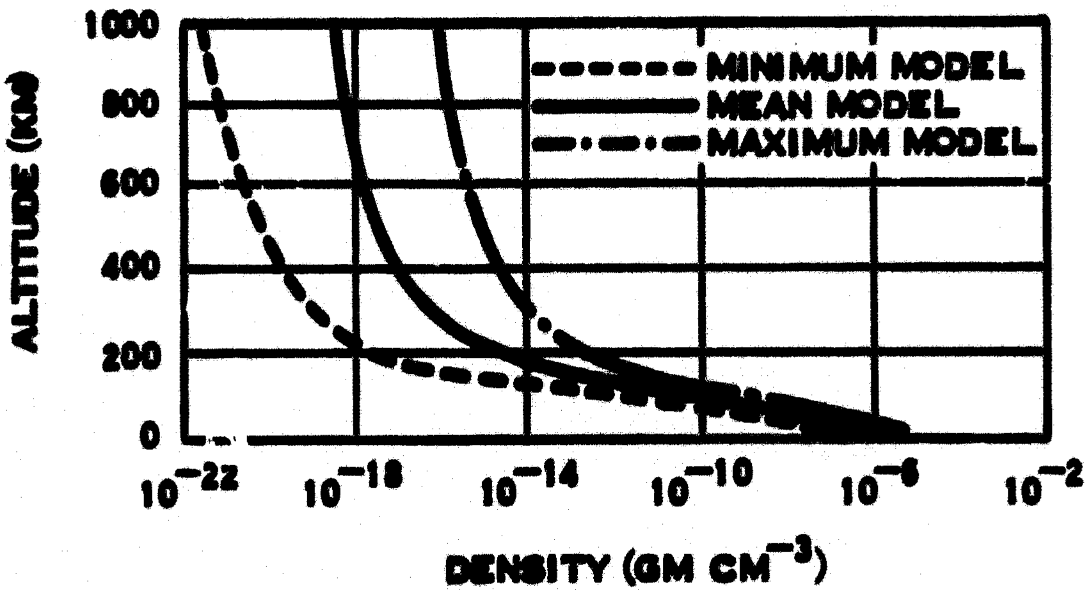

Figure 2-3. Mean and Extreme Density Profiles of the Martian Atmospheres

SECTION 3

PREDICTED SOLAR FLUX

Before discussing the probable solar cyclic variations of the upper atmosphere of Mars, an estimate of the probable variation of solar activity should be made. Of particular interest is the time variation of the 10.7-centimeter radiation flux for the years 1964, 1969, 1971, 1973, and 1975.

The predicted mean and extreme values of the 10.7-centimeter flux (Galbraith, 1967), together with the observed mean and extreme values for 1964 are given in Table 3-1.

From the values given in Table 3-1, it can be seen that the Mariner IV fly-by occurred during a period of low solar activity, while the Mars 1969 fly-by should occur during a period of high solar activity. Consequently, if the upper atmosphere of Mars behaves in a manner similar to the Earth's atmosphere, the derived densities from the Mars '69 fly-by experiments should be considerably greater than those derived from the Mariner IV experiments.

A period of relatively low solar activity is expected in 1973 with a minimum of activity occurring in 1976. Thus, it is likely that the atmospheric density encountered at orbital altitudes by a spacecraft in 1973 will be closer to that derived from the Mariner IV experiments than to that derived from the Mars '69 experiments. Significantly, the atmospheric densities derived from the Mars '69 experiments should provide a close estimate of the maximum density likely to be encountered in the upper atmosphere of Mars.

Table 3-1. Predicted Values of the 10.7-Centimeter Flux

Year	Mean (10^{-22} watts/m^2/cps)	Extreme (10^{-22} watts/m^2/cps)
1964	70	75 to 85
1969	205 to 225	280 to 310
1971	150 to 160	205 to 225
1973	110 to 135	140 to 175
1975	70 to 80	85 to 110

SECTION 4
EXOSPHERE

4.1 TEMPERATURE VARIATION

The empirical relation between the exospheric temperature and solar activity (Vachon and Homsey - 1963) was found to be consistent with the temperature values derived from the Mariner IV data (Vachon-1966). On the basis of this agreement, the empirical relation appears acceptable at this time. Data from the Mars '69 fly-by may provide an opportunity to check the relative validity of the relation for periods of high solar activity. For the present, it is assumed that the empirical relation will provide a reasonable estimate of the exospheric temperature variation as a function of solar activity.

The temperature minima (T_n) are taken to occur at 0400 while the maxima (T_x) occur at 1400 for any value of the 10.7-centimeter solar flux (S). The minima and maxima are obtained by the following formulation:

$$T_n = 1.94S + 275$$

$$T_x = 3.05S + 372$$

where T_n and T_x are in degrees Kelvin, while the 10.7-centimeter solar flux is in units of 10^{-22} watts/m^2/cps. The values of exospheric temperature as a function of solar activity are given in Table 4-1.

4.2 ALTITUDE OF EXOSPHERE BASE

The base of the exosphere (i.e., top of the thermosphere) was initially proposed as a variable dependent on the thermosphere thermal gradient and the exosphere temperature. More recent evaluations indicate that for all practical purposes, the altitude of the base of the exosphere may be relatively constant in time, although intimately related to the selected values of the thermosphere thermal gradient. A comparison between the Harris and Priester

Table 4-1. Martian Exospheric Temperature (°K) as a Function of the 10.7-Centimeter Solar Flux (S)

T (°K)	Solar Flux (S)				
	70	100	150	200	250
Minima	411	469	566	663	760
Maxima	586	677	829	982	1134

(1962) temperature values at 420 kilometers and the temperature value at 2000 kilometers, well within the Earth's exosphere, is given in Table 4-2.

Table 4-2. Comparison of the Harris and Priester Model Temperatures at 2000 km and 420 km

T (°K)	Solar Flux (S)				
	250	200	150	100	70
Minima					
2000 km	1392	1163	944	737	612
420 km	1383	1155	938	732	609
Maxima					
2000 km	2121	1768	1409	1046	827
420 km	2068	1739	1394	1039	822

It thus appears that the base of the exosphere is relatively insensitive to variations in solar activity.

The base altitude of the Martian exosphere is intuitively expected to be lower than it is in the Earth's atmosphere. The upper atmosphere models presented by Hess and Pounder (1966) would suggest an exosphere base altitude of 250 kilometers. Similarly, the model of Smith and Beutler (1967) would suggest an exosphere base altitude of about 340 kilometers.

The empirically derived base altitude of the exosphere will be discussed in Section 5.3 since, as noted above, it is expected to be related to the selected values of the thermosphere thermal gradient.

SECTION 5
THERMOSPHERE

5.1 ALTITUDE OF BASE

The atmosphere of Mars at high altitudes is expected to exhibit a region of temperature increase due to recombination heating. The altitude at which this heat source occurs has recently been estimated at about 90 kilometers (Gross, et. al. - 1966), 100 kilometers (Donahue - 1966), and $<$ 140 kilometers (Chamberlain and McElroy - 1966). Based on evaluations of the Mariner IV data (Vachon - 1966 and Vachon and Lichtenfeld - 1967) the base of the thermosphere was calculated as being around 103 kilometers. For our purposes, the base of the thermosphere is taken as being at an altitude of 100 kilometers. To simplify further calculations, it is assumed that conditions at 100 kilometers remain constant in time and space. Thus, we introduce a fixed boundary condition at 100 kilometers, which contains all of the inherent limitations contained in the same assumption made in regards to the Earth's upper atmosphere, e.g., the density at the boundary altitude is held constant in time and space, although it is known to vary substantially. In the Harris and Priester model (1962), it is found that a fixed boundary exists at an altitude of 120 kilometers. Considering that the Harris and Priester model provides a reasonable fit to the observed conditions at altitudes in excess of 200 kilometers, the assumption of a fixed boundary condition appears permissible as a means of developing models of the atmospheric structure above 200 kilometers for use in orbit decay evaluations.

5.2 <u>THERMAL GRADIENT</u>

The thermal gradient in the thermosphere would be expected to be greatest near the base and to diminish with altitude. The magnitude of the gradient itself is dependent upon the chemical kinetics of the atmosphere. Although it is doubtful that one can use the thermal gradients of the Earth's thermosphere to derive the probable gradients in the Martian thermosphere, it would be interesting to compare such empirically derived values with those from existing models of the Martian upper atmosphere.

The intensity of solar radiation at the Martian orbital distance is about half that incident at the Earth's distance. Since the thermosphere is a by-product of photodissociation and recombination, it will be assumed that the Martian thermosphere thermal gradients are equal to half the value of the Earth's thermosphere thermal gradients. This is an admittedly crude assumption for it totally neglects the differences in the chemical kinetics of the two atmospheres. The thermal gradients for three selected altitude intervals, as well as the equivalent over the three intervals, is given in Table 5-1 for the Earth, and in Table 5-2 for Mars as a function of solar activity.

From the values presented in Table 5-2, it is obvious that the estimates of the altitude variation of the Martian thermal gradients, based on values for the Earth's thermosphere, decrease much more rapidly than those used in Martian atmosphere models. However, based on evaluation of the Mariner IV data (Vachon - 1966, and Vachon and Lichtenfeld - 1967), the thermal gradient over the altitude range of 105 to 138 kilometers, during a period of low solar activity, was found to lie within the limits of $1 \pm 0.5^{\circ}$ K/km.

From the viewpoint of establishing empirical relationships, it would appear more prudent at this time to only use the integrated gradient values between 400 and 100 kilometers. Since the integrated thermal gradients obtained from evaluations of the chemical kinetics (Smith and Beutler - 1967) are in reasonable agreement with the empirically derived values, the latter may therefore provide a relatively reasonable means of relating variations of the thermal gradients as a function of solar activity.

5.3 ALTITUDE OF TOP OF THERMOSPHERE

As noted in Section 4.2, the altitude of the top of the thermosphere, i.e., base of the exosphere, is expected to be relatively constant. However, if the integrated thermal gradients of Section 5.2 are used, together with the exospheric temperature values of Section 4.1 and a fixed boundary at the base of the thermosphere, it is found that the altitude of the base of the exosphere must vary. Thus, either the altitude of the top of the thermosphere must be made variable, or the integrated thermal gradients must be changed

Table 5-1. Altitude Variation of the Thermal Gradient (^{o}K/km) in the Earth's Thermosphere as a Function of Solar Activity

Altitude (km)	Solar Flux (S)				
	250	200	150	100	70
220 to 120					
Minima	8.72	6.83	4.94	3.13	2.06
Maxima	12.65	10.58	8.28	5.70	3.99
320 to 220					
Minima	1.32	0.98	0.74	0.53	0.40
Maxima	3.52	2.64	1.76	0.97	0.58
420 to 320					
Minima	0.24	0.19	0.15	0.11	0.08
Maxima	0.96	0.65	0.35	0.17	0.10
420 to 120					
Minima	3.42	2.67	1.94	1.26	0.85
Maxima	5.70	4.61	3.46	2.28	1.56

Table 5-2. Altitude Variation of the Thermal Gradient ($^{o}K/km$) in the Martian Thermosphere as a Function of Solar Activity

Altitude (km)	Solar Flux (S)						
	250	200	150	100	70	Smith/ Beutler 1967	Weidner/ Hesseltine 1967 Mean
200 to 100							
Minima	4.36	3.42	2.47	1.56	1.03	2.40	2.84*
Maxima	6.33	5.29	4.14	2.85	2.00	2.40	2.84*
300 to 200							
Minima	0.66	0.49	0.37	0.27	0.20	1.06	1.02
Maxima	1.76	1.32	0.88	0.49	0.29	1.06	1.02
400 to 300							
Minima	0.12	0.09	0.07	0.06	0.04	0.28	1.36
Maxima	0.48	0.31	0.17	0.09	0.05	0.28	1.36
400 to 100							
Minima	1.71	1.33	0.97	0.63	0.42	1.27	1.63
Maxima	2.85	2.30	1.73	1.14	0.78	1.27	1.63

*Gradient value given is for an altitude interval of 200 to 150 kilometers to fit the condition of a fixed base altitude for the exosphere. Since the thermal gradients are dependent upon the chemical kinetics of the atmosphere, which were largely ignored, it is felt that modifying the gradient values would be better than introducing a variable exosphere base altitude. Using the integrated gradient values from Table 5-2 together with the exosphere temperature from Table 4-1, the lowest altitude of the exosphere (460 kilometers) was found to be associated with the highest integrated thermal gradient (2.85° K/km) and the highest exosphere temperature (1134°K). Since there is doubt that the exosphere temperature could be this high, and that the integrated thermal gradient is itself much higher than the Smith and Beutler values based on evaluation of the chemical kinetics, it was decided to reject this condition as the basis for scaling. The next lowest altitude of the exosphere (482 kilometers) was found to be associated with an integrated thermal gradient of 1.7° K/km, and an exosphere temperature of 760°K. The relative agreement between the integrated gradient of this case and the model of Weidner and Hasseltine (1967) was taken as a favorable aspect, since their model is based in part on an evaluation of the chemical kinetics. Further, the exosphere temperature value of 760°K is not out of accord with most studies of the chemical kinetics of the Martian upper atmosphere. Although, intuitively, the top of the thermosphere is expected to be lower than it is in the Earth's atmosphere, for the present it is assumed that the top of the thermosphere on Mars is at an altitude of 482 kilometers.

The introduction of a fixed altitude for the top of the thermosphere, with a fixed boundary at 100 kilometers and for the given exospheric temperatures, requires a change in the integrated thermal gradient values. The integrated thermal gradient values for a variable exosphere altitude and for a fixed exosphere altitude are given in Table 5-3.

Table 5-3. Integrated Thermal Gradients (^{o}K/km) in the Martian Thermosphere as a Function of Solar Activity

T (^{o}K)	Solar Flux (S)				
	250	200	150	100	70
Variable Exosphere					
Minima	1.71	1.33	0.97	0.63	0.42
Maxima	2.85	2.30	1.73	1.14	0.78
Fixed Exosphere					
Minima	1.71	1.46	1.20	0.95	0.80
Maxima	2.69	2.29	1.89	1.49	1.26

SECTION 6

VARIATION OF ATMOSPHERIC DENSITY

6.1 DIURNAL VARIATION

The atmospheric density in the Earth's upper atmosphere at 1000 kilometers varies by about one order of magnitude from a minimum at 0400 hours to a maximum at 1400 hours during maximum solar activity periods. Although the magnitude of the diurnal variation of density is about a factor of 3 during periods of low solar activity, occasionally larger variations are encountered even during these periods.

In regard to the Martian atmosphere, it is likely that diurnal variations of density of one order of magnitude are likely to be encountered at orbital altitudes around 1000 kilometers. In a previous estimate of the variation of density on Mars (Vachon-1966 and Vachon and Lichtenfeld-1967), diurnal variations of about two orders of magnitude were suggested as being probable during periods of high solar activity. However, based on more recent evaluations of the probable density variations as a function of solar activity, which are discussed in the following section, it appears that this earlier estimate was overly pessimistic. Indeed, from the density values given in Table 6-1 (presented in Section 6.2), it is seen that the diurnal density variation is about one order of magnitude.

6.2 SOLAR CYCLIC VARIATIONS

The range of density values at 1000 kilometers given in Figure 2-3, Weidner and Hasseltine (1967), is expected to reflect the range of variation likely to be experienced over the full solar cycle. The full range of the Martian density variations at 1000 kilometers is about 3×10^5.

In order to relate the probable distribution of density as a function of solar activity within this range, the Harris and Priester models of the Earth's atmosphere are again considered. The range of density variation at 1000 kilometers from a period of low solar activity (S = 70) to a period of high solar activity (S = 250) is found to be about three orders of magnitude.

Table 6-1. Distribution of Density at 1000 Kilometers in Models of the Terrestrial and Martian Atmospheres

S	Density (g/cc)	Range	Remarks
200 to 250	3×10^{-18} to 1.3×10^{-16}	10^2	Harris and Priester Models of Earth's atmosphere at 1000 km
70 to 100	2×10^{-19} to 1.7×10^{-18}	10^1	
70 to 250	2×10^{-19} to 1.3×10^{-16}	10^3	
Mean to Maximum	5.97×10^{-19} to 1.4×10^{-16}	$2\text{-}3 \times 10^2$	Weidner and Hasseltine models of Mars atmosphere at 1000 km (Figure 2-3)
Minimum to Mean	5.03×10^{-22} to 5.97×10^{-19}	10^3	
Minimum to Maximum	5.03×10^{-22} to 1.4×10^{-16}	3×10^5	

The distribution of density at 1000 kilometers in models of the terrestrial and Martian atmospheres is given in Table 6-1.

From a comparison of the density values and the range of variation given in Table 6-1, several possibilities are suggested. First, the range of density variation in the Martian mean-to-maximum model, Figure 2-3, agrees closely with that expected during a period of high solar activity. Second, the range of density variation in the Martian atmosphere models is almost twice as large as that expected in the Earth's atmosphere. On the basis of the above comparisons, it would appear reasonable to assume the mean-to-maximum density models to be representative of periods of high solar activity. On the other hand, assuming the minimum-to-mean density models to be representative of periods of low solar activity, would appear to introduce a greater range of variation than would be encountered by analogy with the Harris and Priester models.

In order to provide an estimate of the probable variation of the atmospheric structure as a function of solar activity, the mean atmosphere model presented in Section 2 was modified. The modification consisted of altering the thermal structure above 100 kilometers by substitution of the thermosphere thermal gradient values given in Table 5-3, together with the exosphere temperature values given in Table 4-1. This rather simple modification provides a means of estimating the probable variation of the atmosphere as a function of solar activity for any given model. In the case of the selected mean model, the resulting range of density variation as a function of solar activity (Table 6-2) was found to agree closely with that obtained from the Harris and Priester (1962) models.

From the values in Table 6-2, it is seen that the density at 700 kilometers during a period of high solar activity is likely to be almost three orders of magnitude greater than during a period of low solar activity. At an altitude of 1000 kilometers, the calculated density variations indicate a three-order-of-magnitude spread over the full solar cycle. As noted in the preceding section, the diurnal variation of density, as seen in Table 6-2 amounts to about one order of magnitude.

Based on the calculated values for the modified mean model, as well as similar calculations using other models, it appears unlikely that the density at 1000 kilometers will vary by much more than three orders of magnitude over the full solar cycle. However, since the composition of the upper atmosphere is uncertain, the range of density variations must be increased to allow for this uncertainty.

Table 6-2. Variation of the Martian Atmospheric Density (g/cc) at 700 Kilometers as a Function of Solar Activity

	Solar Flux (S)				
	250	200	150	100	70
Minima	5×10^{-17}	2.2×10^{-17}	7×10^{-18}	1.8×10^{-18}	6.2×10^{-19}
Maxima	4.2×10^{-16}	2.2×10^{-16}	8×10^{-17}	2.4×10^{-17}	8.2×10^{-18}

SECTION 7

CONCLUSIONS

Based on the Mariner IV ionospheric experiment data, the base of the thermosphere may be as low as 105 kilometers. The thermosphere integrated thermal gradient is expected to range in value from 0.5° to 3.0° K/km during periods of low to high solar activity respectively.

Estimates of the variations of the atmospheric structure as a function of solar activity indicate:

a. The density at altitudes of about 1000 kilometers is likely to exhibit a diurnal (day-night) variation of an order of magnitude.

b. The atmospheric density at 1000 kilometers during a period of high solar activity is likely to be three orders of magnitude greater than it is during a period of low solar activity.

c. Solar cyclic variations of the atmosphere's density of five and six orders of magnitude at 1000 kilometers are expected to result more from uncertainties in the models than from probable variations of the atmosphere itself.

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